Optimasi *Gain* Pengendali PD Menggunakan *Artificial Bee Colony* untuk Pengendalian Sistem Kren Gantry Kaku

Optimizing the Gains of PD Controller Using Artificial Bee Colony for Controlling the Rigid Gantry Crane System

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Abstract

Control position and reduction of swinging of the payload of a rigid gantry crane system is a challenging work because of under-actuated system. This paper addresses challenges by proposing the artificial bee colony (ABC) algorithm to optimize the gains of the PD controller to form what the so-called the artificial bee colony (ABC)-PD controller. The effectiveness of the proposed control algorithm is tested under constant step functions and compared with Ziegler-Nichols (ZN)-PD controller. Simulation results show that the proposed controller produces slower rise time and peak time, but faster settling time than the ZN-PD controller as well as no overshoot under the predefined trajectories.

Keywords: *Gantry crane system, swing angle, PD gains, ABC*

Abstrak

Kontrol posisi dan reduksi ayunan muatan dari sistem kren gantry kaku merupakan sebuah permasalahan yang menantang karena merupakan sistem yang *under-actuated*. Tulisan ini menyelesaikan tantangan tersebut dengan mengusulkan algoritma *artificial bee colony* (ABC) untuk mengoptimalkan *gain* pengendali PD untuk membentuk yang dinamakan pengendali PD berbasis metode ABC. Keefektifan pengendali yang diusulkan diuji lewat fungsi *step* konstan dan dibandingkan dengan pengendali PD berbasis metode Ziegler-Nichols (ZN). Hasil-hasil simulasi menunjukkan bahwa pengendali yang diusulkan menghasilkan waktu naik dan waktu puncak yang lebih lambat tetapi waktu turun yang lebih cepat juga ketiadaan lonjakan dibandingkan pengendali PD berbasis ZN melalui trayektori yang didefinisikan.

Kata kunci: Sistem kren gantry, sudut ayunan, *gain* PD, ABC

1. Introduction

Gantry crane system, a non-slewing-luffing crane system is most widely used in several work places such as ports, factories, construction sites. This type of crane is designed for repeat motions such as hoisting, transporting which includes longitudinal, transverse motion, and lowering heavy payload, as well as combination of each motion. Schematic of gantry crane system is shown in Figure 1. Gantry crane system can be divided into two subsystems, namely gantry crane and stationary crane framework. Gantry crane incorporates interaction among trolley, wire rope as hoist cable and payload which is manipulated by trolley and hoist mechanism. The payload is grabbed using hook system, which is then hoisted from trolley by means of cable.

The function of cable drum is to wind up or unwind the cable, raises or lowers the payload attached to the hook. The trolley and hoist work simultaneously to perform the task of gantry crane.

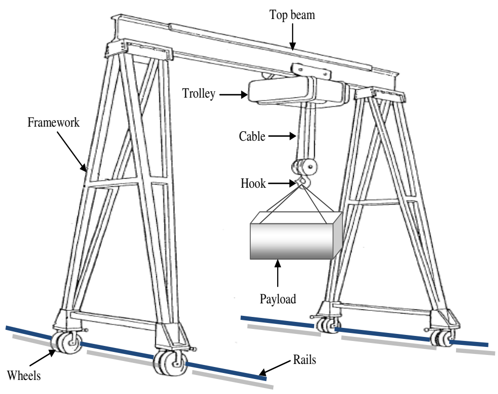

Figure 1. Gantry crane system [1]

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In general, the task performed by a gantry crane is to pick the payload, raise it, move it to target position and lower it down on the crane framework.

Because the traverse motion of trolley during transport operations, the payload has the tendency to swing naturally due to traverse motion of trolley. The swinging motion reduces the speed, accuracy and safety requirements of crane operations. It lowers the speed of crane operations because the payload swing must be avoided before the payload can be safely lowered into specified position. The swings make it difficult to perform alignment, fine position, or other accuracy driven task. Swing effect also causes safety problems to the crane framework. That's why control systems are needed to suppress the effects. If the cable and stationary crane framework are considered as rigid bodies, then the gantry crane system is regarded as a rigid system.

Much attention has been placed on the modeling of dynamics and control of gantry crane system. Khalid et al. [2] have controlled the bridge and gantry cranes by proposing the PD and input shaping controllers and succeeded to achieve good positioning accuracy and significant sway reduction. Hazriq et al. [3]-[4] have studied numerically the dynamic behaviour of a nonlinear gantry crane system by varying the input voltage, cable length, payload mass and trolley mass and controlled the system. They modeled the dynamics using Lagrange's approach and simulated the system through the simulink of Matlab. The rest can be referred to references [5]-[10].

The major contribution of this study is to improve the control capacity of the PD controller (PDC) from the aforementioned previous works. There are several PD tuning methods in the literature (e.g. Ziegler-Nichols (ZN), Cohen-Coon, lambda tuning. However, they do not always lead to an acceptable performance and they may also suffer from some from robustness issues [11].

An optimizer, namely artificial bee colony (ABC) algorithm is proposed to optimize the gains of PDC. That is because this algorithm is a powerful optimization technique, good numerical convergence and multi-dimensional search space compared to other soft computing techniques such as genetic algorithm and particle swarm optimization [12] as well as fuzzy logic and neural network. The combination between the ABC algorithm and PDC is called the artificial bee colony (ABC)-PD controller. This proposed controller is applied to control the position and to reduce the swinging of the payload of rigid gantry crane system. Ziegler-Nichols (ZN) based PD controller is chosen as a benchmark because of its common practice.

The remainder of this paper is organized as follows. Section 2 derives the modeling of rigid gantry crane system. Section 3 describes a typical structure of a PDC with proposed optimizer. Section 4 presents the concept of optimization of PDC via ABC algorithm. Section 5 discusses the control and optimization. Finally, Section 6 concludes this paper.

2. Modeling of Rigid Gantry Crane System

For simplicity of the characteristics of the physical gantry crane system, several assumptions are put forward to the dynamical model. Mass of trolley m_T and payload m_P are modeled as lumped mass which is connected by inextensible hoist cable ℓ_P. Payload and its cable behave as pendulum model as depicted in Fig. 2.

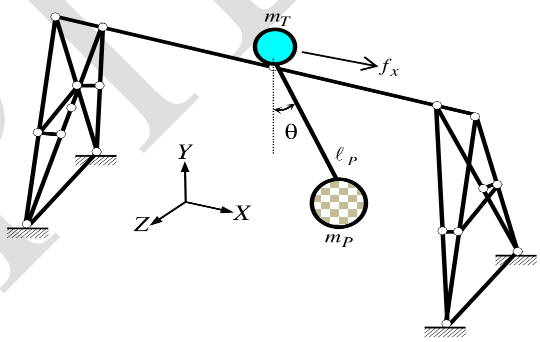

Figure 2. Model of rigid gantry crane system

The payload has one swing angle with respect to the inference frame: θ is denoted as angle between the x_T-axis and $x_T y_T$-plane. The payload swings either small or large swing angles. Friction between trolley and the top beam of crane framework and dynamics of hoist cable and drum in hoist system and hoist drive mechanism are not considered. The structure is treated as a rigid body.

The equations of motion of rigid gantry crane system can be derived by Lagrange's equations, with the following form,

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} + \frac{\partial F}{\partial \dot{q}} = f_i, q = (x_T, \theta), \dot{q} = (\dot{x}_T, \dot{\theta}). \quad (1)$$

All terms of $q = (x_T, \theta)$ are defined as the generalized coordinates to describe the trolley and payload motion. General velocity of the system is $\dot{q} = (\dot{x}_T, \dot{\theta})$. The Lagrangian L is defined as $L = K - P$, where K is kinetics energy and P is potential energy of system. Generalized force is denoted as f_i, where they are f_x, f_y and f_z applied input force for the x, y and z motions respectively.

Total kinetics energy of the system K in terms of generalized coordinates and velocities are the kinetics energy of the trolley and payload,

$$K = K_T + K_P = \tfrac{1}{2} m_T \cdot \dot{r}_T^{\,2} + \tfrac{1}{2} m_p \cdot \dot{r}_p^{\,2},$$
$$K_T = \tfrac{1}{2} m_T \left(\dot{x}_T^2\right), \tag{2}$$
$$K_P = \tfrac{1}{2} m_p \left(\dot{x}_T^2 + 2\dot{\theta}\,\dot{x}_T \ell_P \cos\theta + \dot{\theta}^2 \ell_P^{\,2}\right).$$

Total potential energy of the system is the potential energy of the trolley and the potential energy of the payload,

$$P = P_P = -m_p g\, \ell_P \cos\theta. \tag{3}$$

The energy of damping is expressed as,

$$F = \frac{1}{2} c_x \dot{x}_T. \tag{5}$$

By differentiating the Lagrangian operator L and F with respect to the generalized coordinates q and $\dot{q}$,

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}_T}\right) - \frac{\partial L}{\partial x_T} + \frac{\partial F}{\partial \dot{x}_T} = f_x, \tag{6}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) - \frac{\partial L}{\partial \theta} + \frac{\partial F}{\partial \dot{\theta}} = 0. \tag{7}$$

The nonlinear equation of motion of gantry crane system can be written in Eqs. (8)-(9),

$$(m_T + m_p)\ddot{x}_T + c_x \dot{x}_T + m_p \ell_P\left(\ddot{\theta}\cos\theta - \dot{\theta}^2 \sin\theta\right) = f_x, \tag{8}$$

$$\frac{\ddot{x}_T}{\ell_P}\cos\theta + \ddot{\theta} + \frac{g}{\ell_P}\sin\theta = 0. \tag{9}$$

Equations (8)-(9) are dynamics of gantry crane coupled with dynamics of crane framework and call for some remarks.

1. Equation (8) presents dynamics of trolley motion with the input force, while Eq. (9) is dynamics of payload.
2. Term f_x is input force or driving force for the trolley motion while $(m_T + m_P)$ is mass total from trolley and payload.
3. Term $\ddot{x}_T$ is the acceleration of trolley which appears as the forcing term in the payload dynamics if the input force for gantry crane is set up to be zero.

The input force f_x is generated from the torque of trolley motor. Dynamic of trolley motor can be written as,

$$f_x = \frac{T_x}{r_p} z = \frac{K_T z}{R_T r_p} u_T - \frac{K_T^2 z}{R_T r_p^2} \dot{x}. \tag{10}$$

Equations (8) and (10) are combined to yield,

$$\begin{aligned}(m_T + m_p)\ddot{x}_T + c_x \dot{x}_T + m_p \ell_P\left(\ddot{\theta}\cos\theta - \dot{\theta}^2 \sin\theta\right) \\ = \frac{K_T z}{R_T r_p} u_T - \frac{K_T^2 z}{R_T r_p^2} \dot{x}_T .\end{aligned} \tag{11}$$

Terms in Eq. (11) can be explained as: K_T, R_T, u_T are torque constant, motor resistance and input voltage, respectively while z, r_p are gear ratio and radius of motor pulley.

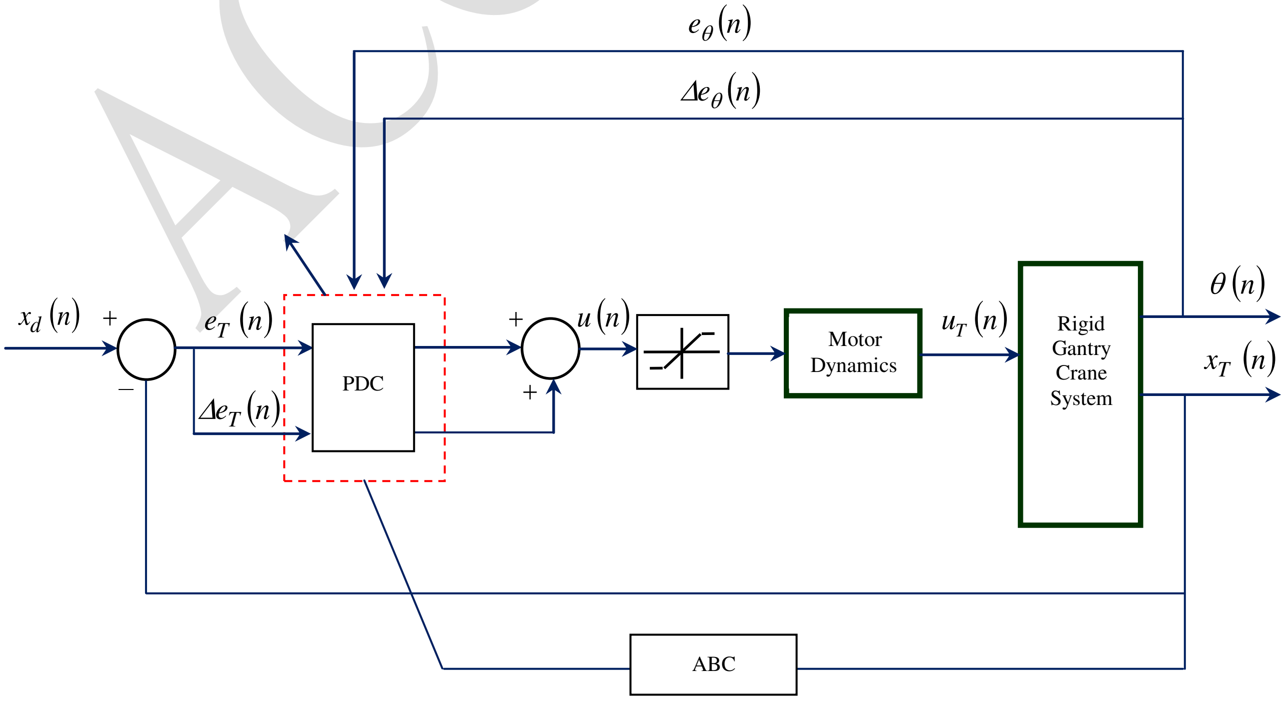

Figure 3. Diagram block of PD controller for rigid gantry crane system

3. Closed-Loop Control System with PD Controller (PDC)

A typical structure of a PDC for controlling the rigid gantry crane system is shown in Fig. 3. It is seen that the system is classified as a double input single output system (under-actuated system). The first input for the PDC is error and error derivative $(e_T(n), \Delta e_T(n))$ of trolley position while the second input is error and error derivative $(e_\theta(n), \Delta e_\theta(n))$ of payload swing. The errors and error derivatives are multiplied by the gains of PDC, namely proportional (K_p) and derivative (K_d) and then combined to form the control signal of PDC as follows,

$$u(n) = K_p\{e_T(n) + e_P(n)\} + K_d\{\Delta e_T(n) + \Delta e_P(n)\}. \quad (12)$$

Terms in Eq. (12) are as follows: $e_T(n), e_P(n), \Delta e_T(n), \Delta e_P(n)$ are errors of trolley position and payload swing as well as their error derivatives, respectively. The value of $u(n)$ is limited by using saturation function before it is sent to the motor. The control action $u(n)$ is then applied to the gantry crane system.

Under any types of system input, the gains in Eq. (12) significantly affect the closed-loop response. Suboptimal gains lead to the system becomes unstable, high overshoot and large steady-state error. The gains must be designed to match the system input (set-point) and the system output by giving the corrective action in terms of control action. Hence, ABC algorithm is employed to optimize those gains. In addition, Eq. (12) also reflects that gain for the errors of trolley position and swinging of the payload are set up similarly and so do the gain of error derivatives. Both gains can be set up separately, but this is intended to make the optimization process efficient.

It is worthy to note that integral action is not required due to the presence of integral (reset) *windup* leading to significant amount of overshoots. Hence, PD controller is an appropriate choice for controlling the system.

4. Optimization of PD Controller via ABC Algorithm

Parameters $\{K_P, K_d\}$ are modeled as foods in artificial bee colony (ABC) algorithm. For the sake of clarity, optimizer for the parameters of PDC using ABC algorithm is called ABC-PD. PDC parameters recalled as $\{K_P, K_d\}$ are initialized randomly in ABC-PD controller. The major phases of this algorithm has been outlined [12], but it is revisited here for a new cost function,

4.1 Initialization

The initial candidate solutions for x are produced for employed bees by using Eq. (12),

$$x_{i,j} = x_j^{min} + \lambda\left(x_j^{max} - x_j^{min}\right), i = 1,\cdots,S, j = 1,\cdots,D. \quad (12)$$

Terms in Eq. (812 can be explained as follows: $x_{i,j}$ is j-th dimension of i-th employed bee, x_j^{min} and x_j^{max} are lower and upper bounds of j-th parameters, respectively, λ is a random number in range of $[0,1]$, S is the number of food sources and D is the number of gains of PDC. The cost function values of i-th the initial solution are calculated using Eq. (13),

$$SSE = \sum_{n=1}^{N}\left(x_T(n) - \hat{x}_T(n) \right). \quad (13)$$

Terms in Eq. (13) are as follows: N is the number of data, $x_T(n)$ is the actual trolley position while $\hat{x}_T(n)$ is the calculated trolley position. The fitness value of Eq. (13) is calculated by using following formula,

$$f_i = \begin{cases} \dfrac{1}{1 + CF_i} & if\ f_i \geq 0 \\ 1 + |CF_i| & otherwise \end{cases}. \quad (14)$$

4.2 Employed bee phase

In this phase, employed bees update the initial candidate solutions using Eq. (15),

$$g_{i,j} = x_{i,j} + \varphi_{i,j}\left(x_{i,j} - x_{k,j}\right), \quad i,k = 1,\cdots,S, \; j = 1,\cdots,D. \quad (15)$$

Terms in Eq. (15) can be explained as follows: $g_{i,j}$ is j-th dimension of i-th updated candidate solution, $x_{i,j}$ is j-th dimension of i-th employed bee, $x_{k,j}$ is j-th dimension of k-th employed bee, term φ is a random number in range of $[-1,1]$. Also, j and k indices are randomly selected among initial solutions so that $i \neq k$ to assure that the initial candidate solutions can be updated. After the solutions are updated, the cost function and fitness values of i-th updated candidate solutions are calculated using Eqs. (14)-(15). If the fitness value of updated candidate solutions is better than fitness value of initial candidate solutions, then the initial candidate solutions are replaced with updated candidate solutions.

4.3 Onlooker bee phase

In this phase, the employed bees communicate with the onlooker bees by calculating the probability of each fitness value as follows,

$$p_i = \frac{f_i}{\sum_{i=1}^{S} f_i}. \tag{16}$$

Based on the probability value, the onlooker bees also randomly improve the candidate solutions in the employed bee phase by using Eq. (16), as well as calculate the cost function and fitness values of i-th updated candidate solutions using Eqs. (15)-(16). If the fitness value of the updated candidate solutions found in the onlooker bee phase is better than fitness value of the solutions in the employed bee phase, the onlooker bee is replaced with the employed bee.

Scout bee phase

If the candidate solutions during the employed bee phase cannot be updated until a predefined number of iterations reaches to the limit, the employed bee becomes scout bee and new candidate solutions are produced by using Eq. (12).

Step by step of optimization process above is depicted in Fig. 4.

parameters of ABC algorithm are shown in Table 1 and Table 2, respectively. Interval for the searching space is $0 \le x \le 100$ for $\{K_P, K_D\}$. Since this paper works on model based control, then Eqs. (9) and (11) are solved using fourth-order Rung-Kutta with sampling time of 0.01 s. Control and optimization processes are performed simultaneously using Matlab.

Table 1. Gantry crane parameters

Parameters	
Trolley mass, m_T	50 kg
Payload mass, m_p	200 kg
Cable length, ℓ_P	1 m
Gravitational acceleration, g	$9.81\ m/s^2$
Initial conditions, $\theta_o, \dot{\theta}_0, \ddot{\theta}_0$	$0^o, 0, 0$

Table 2. Parameters of ABC algorithm

ABC			
Number of iterations	50	Onlooker number	50%
Number of foods	50	Employed bee number	50%
Number of optimized parameters	2	Scout number	1

Time domain responses obtained from ZN-PD and ABC-PD controllers are compared one to another. Control performances in time domain are then assessed in terms of rise time, settling time, overshoot and peak time.

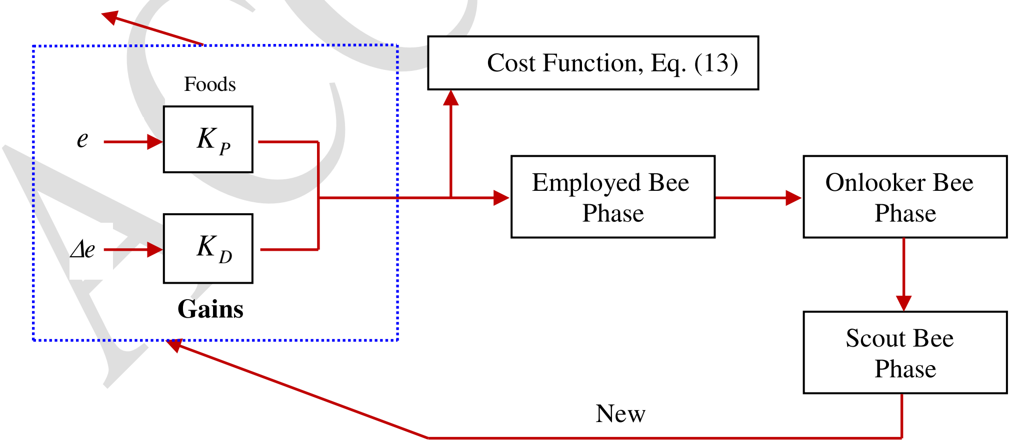

Figure 4. Gains optimization process in ABC-PD controller

5. Results and Discussions

In this section, performance of proposed controller is investigated under constant step function. Other functions such as varying step function and sinusoidal functions are not elaborated in this study. Basic parameters of gantry crane system and

Crane is commanded to track a position in $x \to 12\,m$ by giving a constant step function. The system response for duration 180 s is shown in Fig. 5. The figure depicts that the crane is able to track the commanded position and both controllers have successfully stabilized it with respect to time. This is confirmed by Fig. 6 where the error of both controllers decays to zero.

However, each controller has different performances during the tracking process. ZN-PD controller has faster rise time and peak time than the ABC-PD controller. However, fast rise time and peak time lead to overshoot until it reaches its settling time. In the other side, slow rise time and peak time of ABC-PD controller lead to no overshoot so that settling time can be achieved faster than ZN-PD controller. Details are elaborated in Table 3.

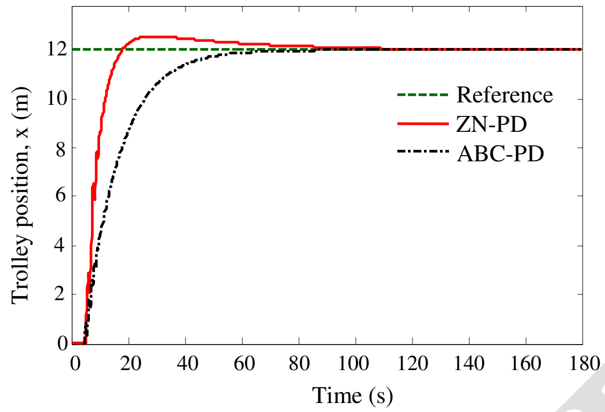

Figure 5. Trolley position under step function

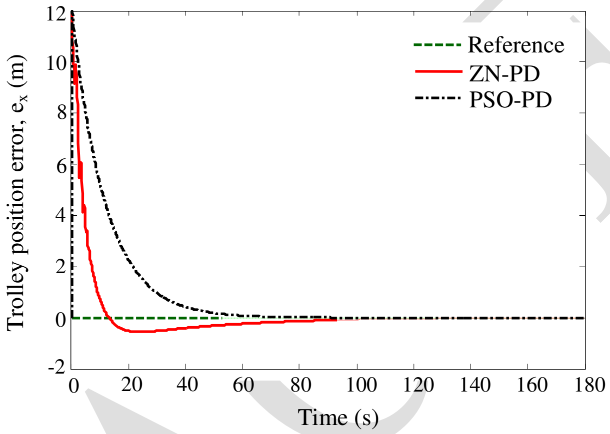

Figure 6. Error of trolley position under step function

Table 3. Controller's performances under step function

Performance	**ZN-PD**	**ABC-PD**
Rise time	8.31	26.23
Settling time	58.44	46.85
Overshoot	4.58	0
Peak time	24.3	177.2

Optimal gains of PD controller are tabulated in Table 4. It is worthy to note that the initial gains are set randomly and it will lead to the change of the optimized gains accordingly. After 50 realizations, it is found that the optimized K_P and K_d of ABC-PD controller are lower than the optimized gains of ZN-PD controller. It explains why the ABC-PD controller has the slow rise time and peak time, fast settling time as well as no overshoot as the function of gain K_P is to increase the rise time of the system response and the function of K_d is to reduce the oscillation.

Table 4. Optimal gains of PD controller under step function

Gains	**ZN-PD**	**ABC-PD**
	Optimized	Optimized
K_p	1.36	0.01
K_d	56.85	20.92

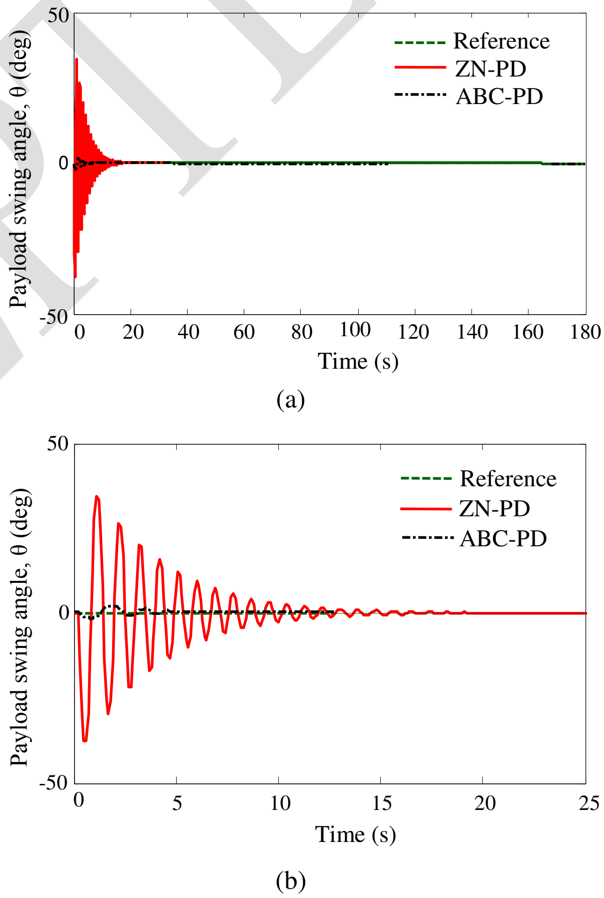

Figure 7. Payload swing angle under for step function (a) time window 0-180 s (b) time window 0-25 s

Control performance in Figs. 5-6 is elaborated by Fig. 7. The figure shows the consequent of fast rise time and peak time of ZN-PD controller. Faster the crane reaches the target position, bigger the swing angle of payload occurs. Large swing angle of payload of ZN-PD controller in Fig. 7 is the consequent of using full nonlinear dynamic model in Eq. 9 and Eq. 11. At this point, control designer can choose whether the trolley moves fast with large swing angle as expense or reasonable speed of trolley with no overshoot. The latter is favorable since it is required for safety in crane operation. Hence, all results confirm that the ABC-PD controller outperforms the ZN-PD controller.

In optimizing the gains, PD controller optimized by ABC algorithm produces cost function as shown in Fig. 8. It displays the cost function with respect to the number of iterations. As observed, the cost exhibits a gradual convergence and seems like a ladder function as the number of iteration increases. However, the cost function starts to converge after the-31st iteration and is steady to a certain value.

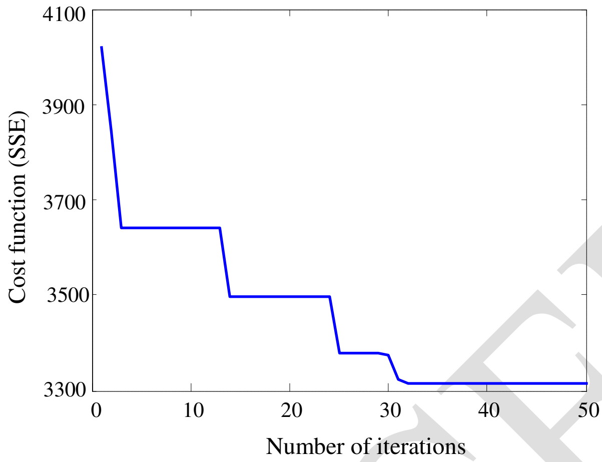

Figure 8. Cost function for step function with respect to number of iterations

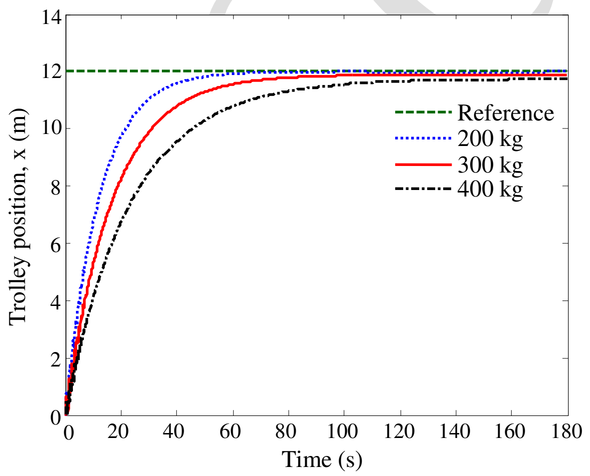

Figure 9. Trolley position under payload mass variation

To test the effectiveness the proposed controller for a more challenging condition, payload mass is varied from 200 kg to 400 kg. Under this condition, the commanded position 4 is fixed and the result is shown in Fig. 9. The crane, as expected, is still able to track the commanded position. However, the figure shows that as the payload mass increases, the rise time and settling time also increases with respect to time. With increased payload mass, performance of ABC-PD controller will deteriorates further.

6. Conclusions

In this paper, a controller namely the ABC-PD is proposed for controlling the rigid gantry crane system. Simulation results show that the proposed controller can improve the performance of closed-loop control system under constant step function. Important conclusions and suggestions from this work are derived below.

- The ABC-PD controller outperforms the ZN-PD controller in terms of fast settling time and no overshoot.
- Control and optimization are still performed under simulation since the ABC-PD controller is computationally expensive for real-time implementation.
- The generated cost function seems like a ladder function.
- The proposed controllers can easily be applied to PID controller, where the gain K_i is included.
- The proposed controllers can be applied to control other dynamic systems.

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